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Studying Damage Accumulation in Martensitic Corrosion-Resistant Steel under Cold Radial Reduction

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Abstract. Cold radial reduction of specimens made of the Kh17N2 corrosion-resistant martensitic steel is studied on a lever-type radial-forging machine (RFM). The mechanical properties of the deformed specimens, the “damage accumulation – strain” relation in the specimens are obtained with the application of hydrostatic and fractographic methods for fractured specimens. The damage of the Kh17N2 corrosion-resistant steel is evaluated as a result of an experimental study considering the data of simulation by a complex finite element model of cold deformation on a lever-type RFM.

INTRODUCTION

The distinguishing feature of the process of cold radial reduction on a lever-type RFM is the ability to achieve a large deformation of billets without intermediate annealing or fractures. The main goal of the study is to evaluate damage accumulation (formation of pores) in a Kh17N2 steel workpiece under deformation on a lever-type RFM with the use of process modeling results and experimental data.

Kh17N2 is a chromium-nickel steel of the martensitic class, with increased corrosion resistance to environmental conditions and some chemical media. The chemical composition of the steel is 0.15÷0.16% C; 0.37÷0.48% Si; 0.51÷0.88% Mn; 15.9÷16.8% Cr; 2.12÷2.17% Ni; 0.008÷0.075% N. This steel is often used in the production of compressor blades of gas turbines and location bracketry working at temperatures above 450 °C [1].

KH17N2 ROD REDUCTION ON A RFM

Kh17N2 corrosion-resistant steel specimens are subjected to cold radial reduction on a lever-type RFM. The rod with the initial diameter of 32.3 mm is subsequently reduced in 8 passes to a diameter of 16.4 mm. The mechanical properties of the rod, namely, flow stress σ_S, ultimate strength σ_U, percentage elongation δ and percentage reduction φ, determined to evaluate the strain dependences of flow stress are presented in Table 1.

Further reduction (the 9th pass) to a diameter of 15.5 mm leads to visible cracks appearing on the rod body. According to this fact, the conclusion is made that the limiting damage value in the process has been reached.

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TABLE 1. Mechanical properties of Kh17N2 steel rod

Rod diameter, mm	ε, %	σ_S, MPa	σ_U, MPa	δ, %	φ, %
32.3	0	790	890	11.3	46
28.6	21.6	950	1040	5.7	43
26.8	31.2	960	1020	4.8	35
22.2	52.8	1000	1070	4.2	34
20.0	61.6	1060	1120	4.1	28
17.0	72.3	1130	1180	3.8	27
16.4	74.2	1140	1210	3.7	27

THEORETICAL DETERMINATION OF THE DAMAGE VALUE

The theoretical basis for the analysis of fractures during large plastic deformations was described in [2-3]. The phenomenological theories discussed in [4-6] have the most general application to the practical evaluation of damage.

During the radial forging of billets, the maximal damage is observed in the axial zone of the billet. Since the axial zone is under monotonic deformation conditions, the value of damage is defined as [7]

$$\psi_i = \frac{\Lambda_i}{\Lambda_{pi}}, \tag{1}$$

where ψ_i is the plasticity resource utilization factor on the i^{th} pass of deformation; Λ_i is the increment of shear strain as the metal particles go through the deformation zone in the i^{th} pass of deformation;

$$\Lambda_i = 2\sqrt{3}\, ln\left(\frac{d_{i-1}}{d_i}\right), \tag{2}$$

where d_{i-1}, d_i are rod diameters in the $(i-1)^{th}$ and i^{th} passes of deformation, respectively; Λ_{pi} is metal plasticity in the i^{th} pass of deformation.

With a sufficient accuracy, the plasticity of the metal can be defined as

$$\Lambda_{p_i} = \chi \cdot exp\left(\lambda \cdot k_{avg_i}\right), \tag{3}$$

where k_{avg_i} is the average value of the stress state index in the i^{th} pass of deformation; χ and λ are the coefficients of the plastic properties of the metal.

The stress state index k is defined as the relation of the value of mean stress to the value of effective stress. It is a nondimensional quantity, which uniquely characterizes the stress state during plastic deformation and allows one to compare the stress state of materials with different levels of strength properties.

In order to determine the damage value after several passes of deformation, one needs to use the expression

$$\psi = \sum_{i=1}^{n} \psi_i, \tag{4}$$

where n is the number of deformation passes.

The modeling of Kh17N2 steel rod reduction allows us to obtain the values of the stress state index and to find the value of damage after forging passes and its total value. On the whole, the complex model of deformation on a lever-type RFM offers mechanical variables of the deformation zone based either on the method of solving approximate equilibrium equations and the plasticity condition or on the FEM, depending on the problem statement [7-9].

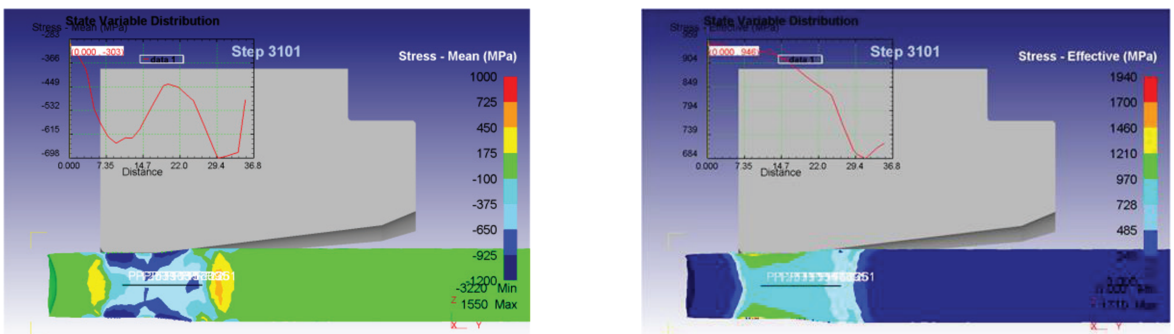
Table 2 lists the calculation results of the stress state index k_i, the value of damage Ψ_i, the total value of damage $\Sigma\Psi$ for different values of the shear strain increment Λ_i.

TABLE 2. Calculation results for strain parameters in each pass

Reduction Ø mm - Ø mm	Λ_i	k_{avgi}	Ψ_i	$\Sigma\Psi$
32.3 – 28.6	0.453	-1.306	0.141	0.141
28.6 – 26.8	0.225	-1.233	0.076	0.217
26.8 – 24.5	0.311	-1.261	0.102	0.319
24.5 – 22.2	0.341	-1.271	0.11	0.429
22.2 – 20.0	0.362	-1.278	0.116	0.545
20.0 – 18.6	0.251	-1.244	0.084	0.629
18.6 – 17.0	0.312	-1.264	0.102	0.731
17.0 – 16.4	0.124	-1.206	0.044	0.775

As it follows from Table 2, the cold radial reduction process on the lever-type RFM is characterizing by a favorable scheme of the stress-strain state. This confirms the sufficiently great negative values of the stress state index in all the passes, and this, in turn, increases the plasticity of the material being processed and provides large total reduction without billet fracture. The calculated value of accumulated damage is in agreement with the experimental data (Table 1) and, besides, it is proved by the specimen cracking when the specimen reduction reaches the diameter of 15.5 mm.

On the example of one of the forging passes, FE solution results are presented, which allow us to evaluate the overall behavior of the process. Figure 1 a and b shows, respectively, the distribution of the mean stress and the effective stress in the longitudinal section of the deformation zone. The upper forging die is in the lowermost position (the other dies are not shown).



(a) (b)

FIGURE 1. The longitudinal section of the deformation zone: mean stress distribution (a); effective stress distribution (b)

EXPERIMENTAL METHODS FOR DAMAGE EVALUATION

The main criteria evaluating the level of the development of the fracture zones with the progress of plastic deformation is the value of damage Ψ. With Ψ no greater than 0.2 ÷ 0.3, the development of dislocation structures and the formation of elastic defects in the form submicrocracks and micropores occur in the metal under deformation, which are healed during recrystallization annealing. With Ψ = 0.6 ÷ 0.7, energetically stable defects, which are not removed by recrystallization, arise and remain in the metal. With a subsequent increase in damage, closely-spaced micropores join to form cavitations in the form of cracks and pores, and this leads to the physical destruction of the billet (Ψ=1). The changes in the density of the metal during deformation are caused by the development of the continuity of inner microdefects, which is considered as a factor of damage [10, 11].

The phase structure of the Kh17N2 steel specimens in the initial state and after a maximum reduction of 75% is determined by X-ray structural analysis on a Shimadzu XRD-7000 X-ray diffractometer with monochromatic Kα-radiation from a chromium anode. The obtained diffraction patterns are displayed in Fig. 2. As is seen, the diagrams for the specimen in the initial state and at the maximum reduction are almost identical. There are reflections only from the α-phase (martensite) on them. The difference in the ratios of the X-ray reflections for the specimens in the initial state and after the deformation can be explained by the appearance of a crystallographic texture during deformation. Therefore, the strain up to 75% does not produce phase transformations in the Kh17N2 steel, and this testifies that, during the cold radial reduction of the Kh17N2 steel, there are no density changes due to the $\gamma \rightarrow \alpha$-phase transformation, and plastic loosening is caused only by the accumulation of strain-induced defects (micropores).

For the precise measurement of density, the differential hydrostatic weighing method is applied [12]. The weighing is carried out on an Ohaus Adventurer precision analytical balance, whose measurement error is 0.001 g. Statistical analysis of the experimental data after density calculation is performed for a small selection ($n < 25$) with a confidence probability of 0.95. As a result, with the increasing reduction of the Kh17N2 steel specimens on the RKM, a monotonic decrease in density can be observed (up to a strain of approximately 40%). When the strain exceeds 40% (cross-section narrowing), the stage of saturation occurs while the density remains constant (with a slight elevation), despite the strain increase (Fig. 3).

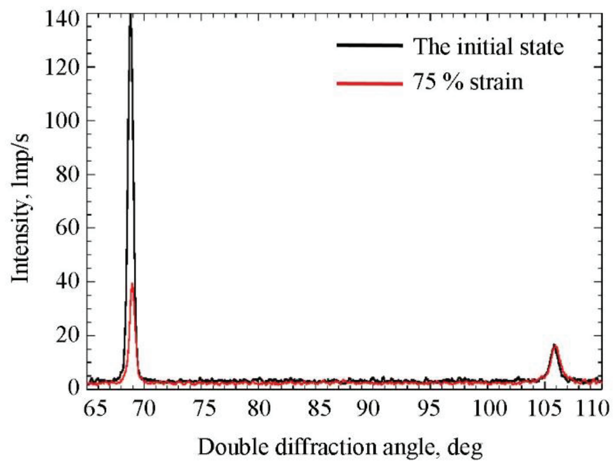


FIGURE 2. Diffraction patterns for Kh17N2 steel specimens (——— - the initial state; ——— - 75% strain)

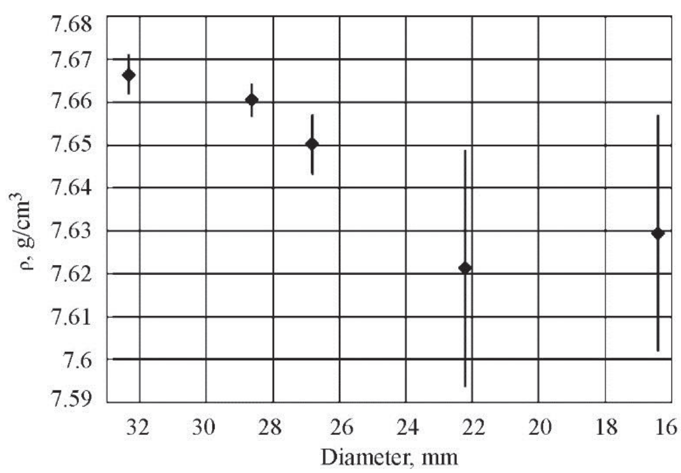
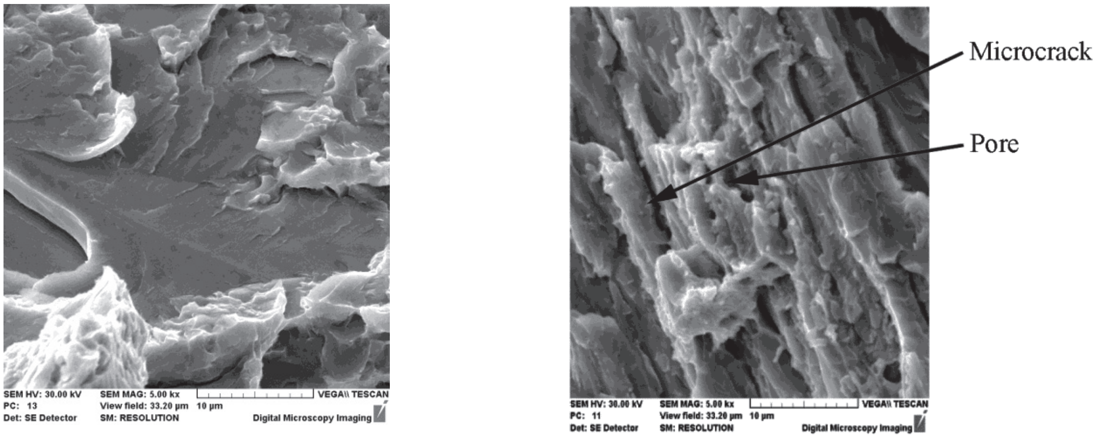


FIGURE 3. The density vs diameter graph for deformed Kh17N2 steel specimens

To render and evaluate accumulate damage and to verify the density-strain graph obtained by the hydrostatic weighing method, a fractographic study of specimen fracture is carried out on a Tescan Vega II XMU scanning electron microscope [13]. The results of the fractographic examination of the brittle fractures of Kh17N2 steel specimens agree well with the data on the density of the corresponding specimens (Fig. 4). It is obvious from Fig. 4a that the structure of the fracture of the initial (non-deformed) specimen is represented by cleavage facets, with an almost complete absence of pores and microcracks. In the fracture of the rod forged with a maximum reduction of 74.4% (Fig. 4b), pores and microcracks are clearly visible, which loosen the material and decrease its density.



(a) (b)

FIGURE 4. Fractographs of Kh17N2 steel rod cracks (×5000): a non-deformed specimen with a diameter of 32.3 mm (a); a deformed specimen with a diameter of 16.4 mm (b)

CONCLUSION

1. The main feature of the cold radial reduction process performed on a lever-type RFM is the possibility to attain a large strain in the deformation of martensitic corrosion-resistant billets. This fact is explained by the favorable scheme of the stress-strain state, and this corresponds to uniform compression with a significantly negative value of the stress state index in each pass of deformation.
2. The simulation of accumulated damage with the use of the FE model of deformation on a lever-type RFM has been verified with a sufficient accuracy by the conducted experimental study.
3. The results of the fractographic analysis of the Kh17N2 steel agree well with the data on the specimen density obtained by the hydrostatic weighing method.

REFERENCES

1. F. F. Khimushin, *Stainless Steels* (Metallurgy, Moscow, 1967), 798 p.
2. V. L. Kolmogorov, *Plasticity and Fracture* (Metallurgy, Moscow, 1977), 337 p.
3. V. L. Kolmogorov, *Mechanics of Metal Forming* (Metallurgy, Moscow, 1986), 668 p.
4. V. L. Kolmogorov, B. A. Migachev and V. G. Burdukovsky, *Phenomenological Model of Damage Accumulation and Fracture under Different Loading Schemes* (UB RAS, Ekaterinburg, 1994), 104 p.
5. A. A. Bogatov, O. I. Mizhiritsky and S. V. Smirnov, *Plastic Resource of Metals in Forming* (Metallurgy, Moscow, 1984), 144 p.
6. A. A. Bogatov, Mechanical Properties and Models of Metal Fracture (UPI, Ekaterinburg, 2002), 329 p.
7. A. P. Karamyshev, I. I. Nekrasov, V. S. Parshin, A. I. Pugin and A. A. Fedulov, Metallurgist **53**, 623–626 (2009).
8. A. P. Karamyshev, I. I. Nekrasov, V. S. Parshin, A. I. Pugin and A. A. Fedulov, Metallurgist **11**, 13–115 (2015).
9. A. P. Karamyshev, I. I. Nekrasov, V. S. Parshin and V. A. Systerov, Metallurgist **53**, 162–166 (2009).
10. A. P. Karamyshev, I. I. Nekrasov, V. S. Parshin, A. A. Fedulov and A. I. Pugin, Metallurgist **56**, 115–118 (2012).
11. A. P. Karamyshev, I. I. Nekrasov, A. V. Nesterenko, V. S. Parshin, S. V. Smirnov, A. A. Fedulov and V. P. Shveikin, "Studying the Damage of Ingots under Plastic Deformation on a Lever-Type Radial Forging Machine", in *Mechanics, Resource and Diagnostics of Materials and Structures (MRDMS-2016) 1785*, AIP Conference Proceedings, 2016, (American Institute of Physics Inc., Melville, NY, 2016).
12. S. V. Smirnov and T. V. Domilovskaya, Metals **5**, 68–76 (2002).
13. V. I. Levit, S. V. Smirnov and A. A. Bogatov, The Physics of Metals and Metallography **4** (54), 787–792 (1982).